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Technical Memorandum 33-787

Final Report: Apollo Experiment S-217 IR/Radar Study of Apollo Data

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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Final Report: Apollo Experiment S-217 IR/Radar Study of Apollo Data

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Preface

The work described in this report was performed by the University of Utah Research Institute, the Aerospace Division of the Boeing Company, and the NEROC Haystack Observatory, all under the cognizance of the Space Sciences Division of the Jet Propulsion Laboratory.

Acknowledgments

Personnel from the Astrogeology Branch of the United States Geologic Survey provided many useful inputs to our studies. Their contributions are best noted by thanking the following co-authors: H. Masursky, the 52 crater paper and the Apollo 15 and 16 landing site papers; Michael Carr, the Apollo 15 landing site paper; Daniel Milton, the Apollo 16 landing site paper; Keith Howard, the Mare Serenitatis paper; Carol Ann Hodges and Donald Wilhelms, the Aristarchus Plateau paper.

G. L. Tyler of Stanford provided many useful inputs to our studies; he is a co-author of the 52 crater paper, the Mare Serenitatis paper, and the compilations along the Apollo bistatic radar tracks.

Three of our co-investigators were funded by the following sources: H. Moore and G. Schaber were funded under Apollo Experiment S-222, which was performed by the Branch of Astrogeologic Studies of the United States Geological Survey, with Dr. Henry J. Moore as the Principal Investigator. Ewen Whitaker of the Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona, was funded by NASA Grant NSG-7014. Mr. Whitaker provided the color-difference photography, which is particularly critical for the interpretation of surface chemistry.

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Abstract

This is the final report on Apollo Experiment S-217, *IR and Radar Study of Apollo Data*, an experiment using Earth-based remote-sensing radar, infrared eclipse, and color-difference data to deduce surface properties not visible in Apollo photography. The Earth-based data provided information on the small-scale (centimeter-sized) blockiness and on the surface chemical composition (titanium and iron contents) of the lunar surface. These deduced surface properties complemented the new Apollo photography, leading to refined geologic interpretations of the lunar surface. Joint studies were conducted with Apollo Experiment S-222 (Photogeology) on a number of lunar areas. Results of these joint studies appear in the open literature. The work performed under Apollo Experiment S-217 is summarized in this report.

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I. Introduction

The Apollo Experiment S-217, *IR/Radar Studies of Apollo Data*, one of the Apollo Photo-Data Analysis Experiments, concentrated on the use of remote-sensing (primarily Earth-based) observations of the Moon to determine surface properties not inherently associated with photography. An important accomplishment was the joint studies with Apollo Experiment S-222, *Photogeology*. The geologic interpretation of lunar features was enhanced by knowledge of surface conditions deduced from the remote, nonphotographic sensors. The photogeologic interpretations similarly enhanced understanding of the remote sensed data. Apollo Experiment S-217 started in June 1972 and ran until the spring of 1976.

A. Background

The lunar surface became the subject of intense study in the 1960s, with the advent of space flight. The manned landings and surface samplings of the Apollo missions were the culmination of a series of space flights from the Ranger and Lunar Orbiter photographic missions to the Surveyor surface-sampling missions. Scientific interest kept in step with these space advances.

The initial focus for the S-217 work was provided by the Symposium on the Geophysical Interpretation of the Moon, chaired by Eugene Simmons of M.I.T., and held at the Lunar Science Institute in July 1969, immediately following man's first landing on the Moon. Our first study concentrated on the thermal, radar, and geologic interpretation of 52 craters (Ref. 1). This initial effort, which showed that the infrared and radar data complemented the geologic interpretation of a range of the lunar crater types, led to the S-217 experiment proposal and the work that is reported here.

B. Work Performed in S-217 Experiment

The work performed in the S-217 experiment (and in the cooperative effort with the S-222 experiment) extended that first study to other areas of the Moon, focusing on the Apollo landing sites. Interpretations of the Apollo 15 landing site at Hadley Rille and the Apollo 16 landing site at the Descartes have been reported in Refs. 2 and 3. A remote sensing analysis of the Apollo 17 landing site at Taurus-Littrow and the entire Mare Serenitatis basin have also been reported (Refs. 4, 5, and 6).

In addition to the Apollo landing sites, selected areas of the Moon were studied because of their unusual geology and remote sensing signatures. The unique radar and color signatures of the lava flows in Mare Imbrium were discussed by Schaber, et al., (Ref. 7), while the unusual

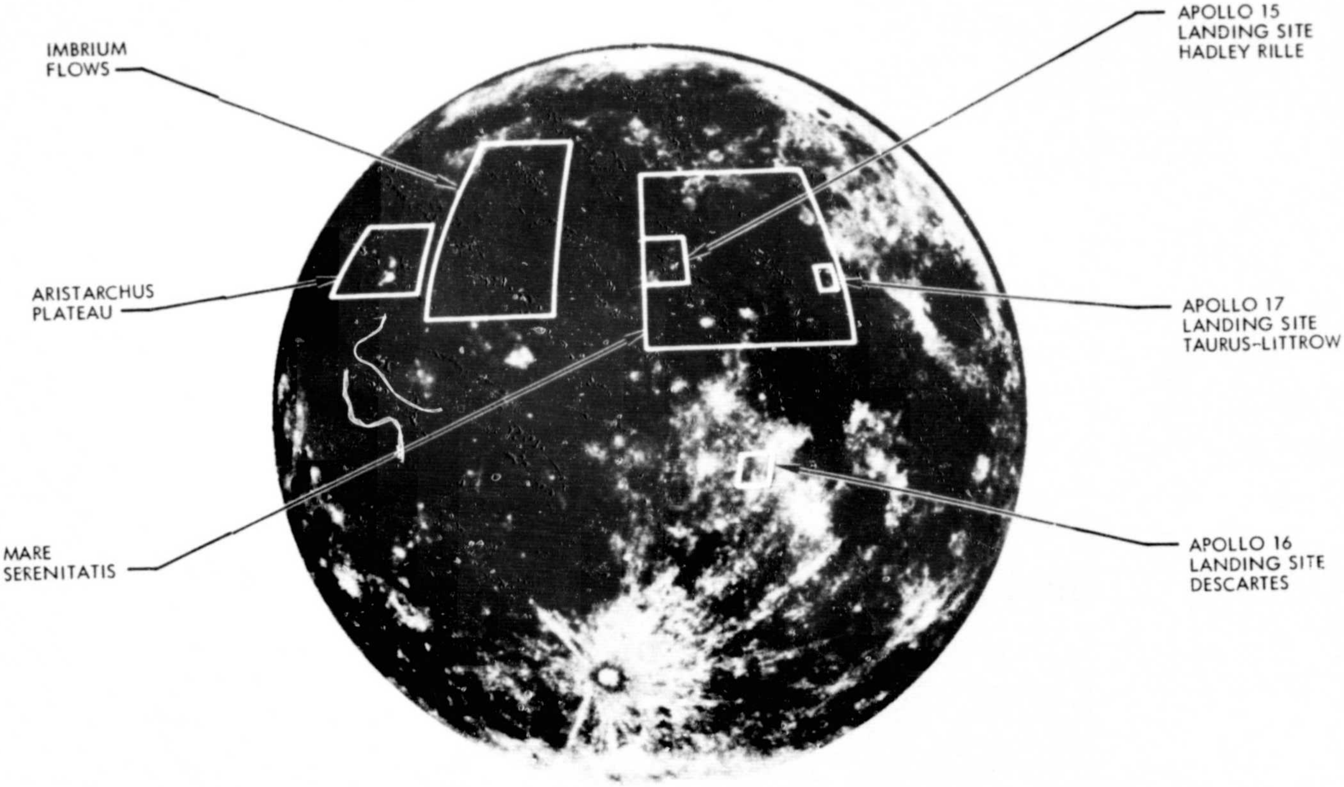

Fig. 1. Cooperative study areas of the S-217 and S-222 Experiment Teams

Table 1. Study areas of the S-217 Team

Area	Latitude	Longitude	Reference
Apollo 15 landing site at Hadley Rille	20°N to 28°N	0° to 8°E	18
Apollo 16 landing site at Descartes	7°S to 12°S	14°E to 19°E	2, 3
Apollo 17 landing site at Taurus-Littrow	18°N to 22°N	28°E to 32°E	6
Mare Serenitatis	10°N to 40°N	0° to 35°E	4, 5, 24
The Imbrium Flows	16°N to 48°N	14°W to 38°W	7
The Aristarchus Plateau	20°N to 32°N	40°W to 58°W	8
Correlations along Apollo bistatic radar tracks			9, 10

remote-sensing signatures of the Aristarchus Plateau have been studied in great detail by Zisk, et al., (Ref. 8). Also, radar, infrared, and color-difference data were compared with the Apollo 15 and 16 bistatic radar data (Refs. 9 and 10). A study of the techniques of factor and cluster analysis applied to lunar data sets was performed by Shorthill, et al., (Ref. 11). Figure 1 shows the areas studied by the combined S-217/S-222 teams. Table 1 summarizes the joint study areas.

C. Future Work

The work performed under Apollo Experiment S-217 showed that Earth-based and orbital observations of the lunar surface can indeed be correlated with more conventional visual photogeologic data to better understand the geology, surface properties, and chemistry of an extraterrestrial body. During S-217, we started with analysis of the Apollo landing sites where in situ measurements and returned sample data were available, and extrapolated such data to other scientifically interesting (but unsampled) regions of the moon. Much work needs to be done with regard to extending the remote sensing data synthesis techniques developed during S-217 (and S-222) to other lunar areas of interest. Examples of possible research topics for the near future are:

(1) Analysis of the unique low radar reflectivity observed around the outer rims of a number of large lunar craters of diverse age (e.g., Aristillus, Cassini, Plato, Aristoles). Such low radar reflective rings may represent variations in physical and/or chemical properties of materials ejected from depth during the individual cratering events.

(2) Spectral reflectivity data and color composite photographs of the lunar surface have revealed only a very few extremely red surface features. One of these features is the Gruithuisen domes located 35°N and 40°W. These domes have long been thought to represent very silicic volcanic materials. A detailed evaluation of spectral reflectivity data and photogeologic data of these features would be of significant interest. No such silicic materials were sampled by any of the lunar landing missions.

(3) The correlation of radar reflectivity and color with mappable flow scarps in Mare Imbrium during S-217 was extremely rewarding, but still poorly understood with regard to the physical processes involved.

The modulation of remotely sensed data by surface chemistry needs further study. The correlation of greatly reduced radar backscatter with blue mare color in Mare Imbrium is seen to be reversed in the case of the Aristarchus Plateau area where the correlation of weak radar return is from a red surface. The inference has been that a highly absorbing surface material with elevated iron-titanium content is responsible for the high radar absorption while diverse valence states of titanium and iron ions in glasses (black glass—orange glass) is responsible for the color changes. This interpretation needs further investigation where similar correlations exist in other lunar areas. The low radar return/red color correlation appears restricted (on the lunar nearside hemisphere) to regions of dark mantle of probable pryoclastic origin and extreme age (3.75 billion years). Other low-albedo regions such as the Haemus Mountains and the Sulpicius Gallus region (eastern edge of Mare Serenitatis) need to be examined further using all remote sensing data currently available. Spectral reflectivity, and high-resolution remanent magnetization (1–2 km) data from Lunar Polar Orbiter should provide additional valuable information regarding the chemistry of these deposits.

Other questions remain unanswered. For example, what is the physical significance of the bright, fuzzy spots in the 3.8-cm maps that were noted as surface type II in our 52 crater paper? What is the geological significance of the surface properties that caused the unusual color and radar scattering around crater Plato and in the highlands that lie along the northern rim of the Imbrium Basin? What is the geologic significance of the subtle color differences that appear in eastern Mare Tranquillitatis?

The need to study areas away from the Apollo tracks has already been demonstrated by our study of the Aristarchus Plateau and a recent study of Mare Humorum by Pieters, et al., (Ref. 12). Study of areas away from the Apollo tracks is necessary to provide a basis for interpretation of Lunar Polar Orbiter data. When the Lunar Polar Orbiter becomes a reality, our attention will focus on the global lunar problems.

The synthesis of lunar data will have to deal with larger volumes of more diverse measurements. Future systematic treatments of these larger volumes of data will require more sophisticated mathematical techniques of statistical analysis. The factor/cluster analysis that was proven by the S-217 study of Mare Serenitatis with four data sets needs to be applied to other lunar areas with more data sets.

The joint work with geologists proved valuable in interpreting lunar surface conditions. Future synthesis of lunar data should rely heavily upon the geologic mapping expertise that has been built up for the Surveyor, Lunar Orbiter, and Apollo missions.

II. Data Sets

The S-217 work was primarily an interpretation of existing data sets (no new data were produced by this experiment). Most reports and scientific articles produced by the joint S-217/S-222 teams contain sections describing these data sets.

Two prime data sets are the 3.8-cm and 70-cm radar maps of the Moon (Refs. 13, 14, and 15). Other prime data sets are the infrared eclipse maps (Ref. 16) and the color difference photography of Whitaker (Ref. 17). All of these data are shown in Figs. 2, 3, 4, and 5. All of these data sets were also converted to digital formats by the Image Processing Laboratory (IPL) at the Jet Propulsion Laboratory, as described in the Appendix.

The data sets above emphasize surface properties complementary to the Apollo photography. The 3.8-cm and 70-cm radar maps emphasize surface roughness with centimeter scales, slopes, and surface electrical losses. The infrared eclipse maps emphasize surface blockiness. The color-difference photographs emphasize surface chemical composition.

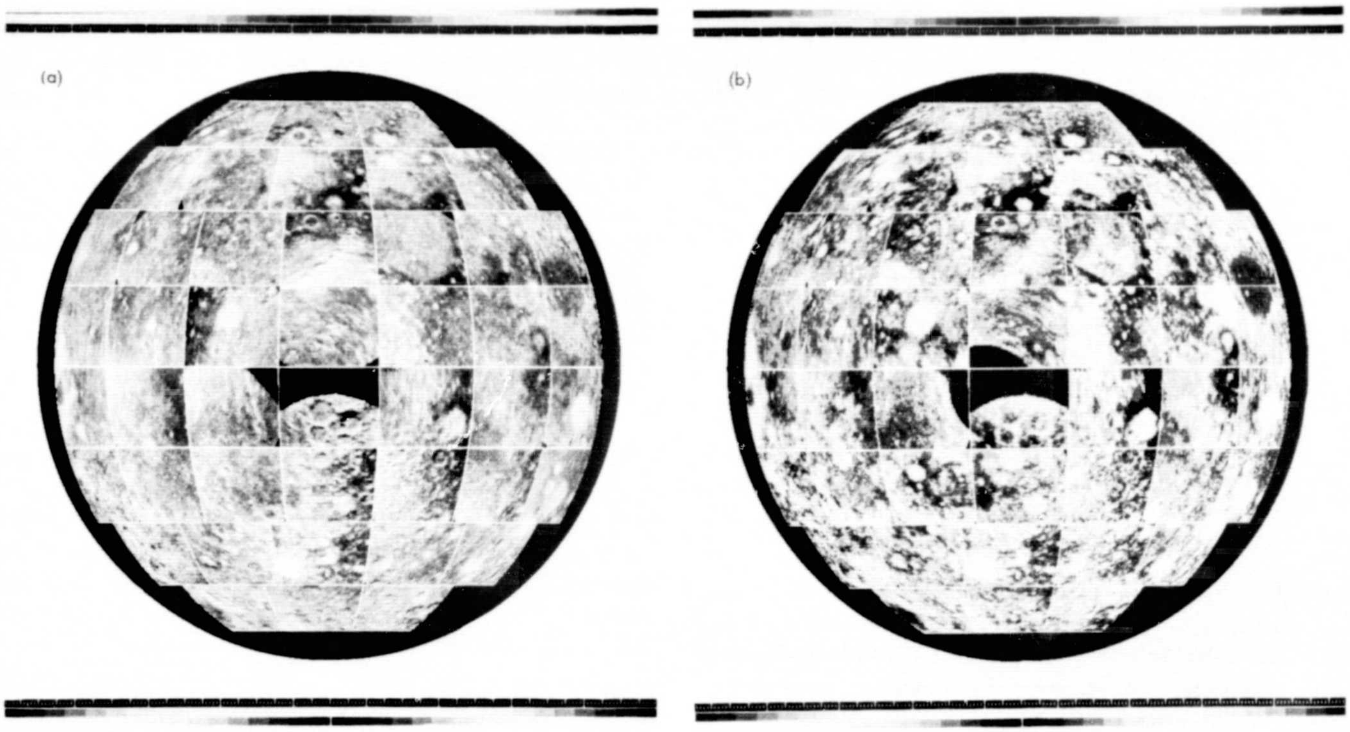

Fig. 2. Data sets for the S-217 Experiment: 70-cm polarized and depolarized radar echoes (provided by T. W. Thompson; see Ref. 15)

III. Results

Our prime objective was to interpret various remote-sensed lunar data sets to augment the knowledge gained from Apollo orbital photography. The problem was attacked by interpreting remotely-sensed data sets for the areas surrounding the Apollos 15, 16, and 17 landing sites. In addition, three larger areas—Mare Serenitatis, the Imbrium Flows, and the Aristarchus Plateau—were studied. The Mare Serenitatis basin provided a subject for cluster and factor analysis, a recent sophisticated statistical technique first applied to lunar data.

To present this summary coherently, the descriptions of these studies will be given in the following order: the paper on the 52 craters will be discussed first because it sets the stage for the S-217 experiment; the Apollo landing sites will be discussed second; third, the larger areas will be discussed—Mare Serenitatis, Imbrium Flows, and the Aristarchus Plateau.

A. The Initial Study of 52 Craters

The initial study of 52 craters (Ref. 1), was conducted in 1969 and 1970 at the Symposium for the Geophysical Interpretation of the Moon (held at the Lunar Science Institute). The major results of this study are summarized in Table 2; the article states:

> Between 1000 and 2000 infrared (eclipse) and radar anomalies have been mapped on the nearside hemisphere of the Moon. A study of 52 of these anomalies indicates that most are related to impact craters and that the nature of the infrared and radar responses is compatible with a previously developed geologic model of crater aging processes. The youngest craters are pronounced thermal and radar anomalies; that is, they have enhanced eclipse temperatures and are strong radar scatterers. With increasing crater age, the associated thermal and radar responses become progressively less noticeable until they assume values for the average lunar surface. The last type of anomaly to disappear is radar enhancement at longer wavelengths. A few craters, however, have infrared and radar behaviors not predicted by the aging model. One previously unknown feature—a field strewn with centimeter-sized rock fragments—has been identified by this technique of comparing maps at the infrared, radar, and visual wavelengths.

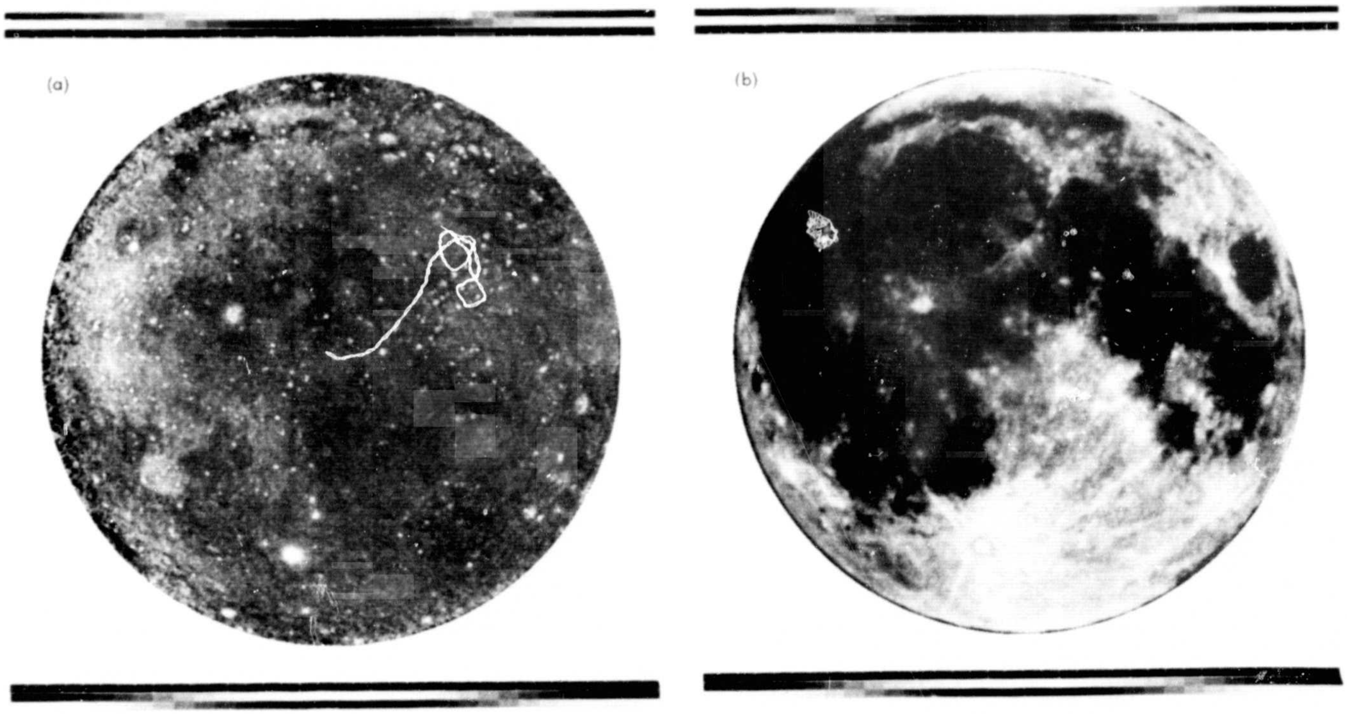

Fig. 3. Data sets for the S-217 Experiment: infrared eclipse temperatures and full-Moon albedo (provided by R. W. Shorthill; see Ref. 16)

This work established infrared eclipse temperatures and radar maps as indicators of surface properties, and complemented geologic interpretation of the photography. This first paper also led to a good working relationship where lunar synthesis took place in a workshop atmosphere and publication of scientific articles was the primary output of the work, and led further to the S-217 proposal and the subsequent work reported here.

B. The Apollo 15 Landing Site at Hadley Rille

Our attention was focused on the Apollo landing sites for the obvious reason that man landed there and could bring back ground-truth information about the lunar surface. The question asked was how the remote sensing data would agree with the astronauts findings? Our report on the Apollo 15 landing site at Hadley Rille was given by Zisk, et al., (Ref. 18), who studied the area bounded by 20°N and 28°N latitude and 0° and 8°E longitude.

The infrared, radar, and photographic evidence indicated that the Appennine crest could be interpreted as a smooth, dense surface with a dielectric constant near 4.0, and with no more than the average-surface and near-surface rocks of centimeter size. These surface conditions are consistent with the geologic interpretation that these mountains are very old. The remote sensing data suggests a fine-grained, deep regolith over the Appennine backslope, consistent with a deposit of fine-grained material. Examination of the remote sensing signatures of the crater Hadley C argues for an unusual geology for the crater.

In concluding this study, Zisk, et al., (Ref. 18), noted that "useful geologic information can be drawn from Earth-based radar and infrared studies of the lunar surface since the measured quantities are strongly influenced by structure on a scale much finer than basic instrumental resolution."

This study of the Apollo 15 landing site was completed before the S-217 experiment was funded. However, this study is described here because it and the 52 crater paper laid the groundwork for the study of other Apollo landing sites when S-217 was funded.

C. The Apollo 16 Landing Site at Descartes

Work on the Apollo 16 landing site is reported in companion papers by Zisk, et al., (Ref. 3), and by Zisk and Moore (Ref. 2) in the Apollo 16 Preliminary Science Report (Ref. 19). The first article interpreted an area bounded by 14°E and 18°E longitude and by 7°S and 11°S latitude, surrounding the Apollo 16 landing site at 8°59'S, 15°31'W. This work concentrated on two questions: (1) is

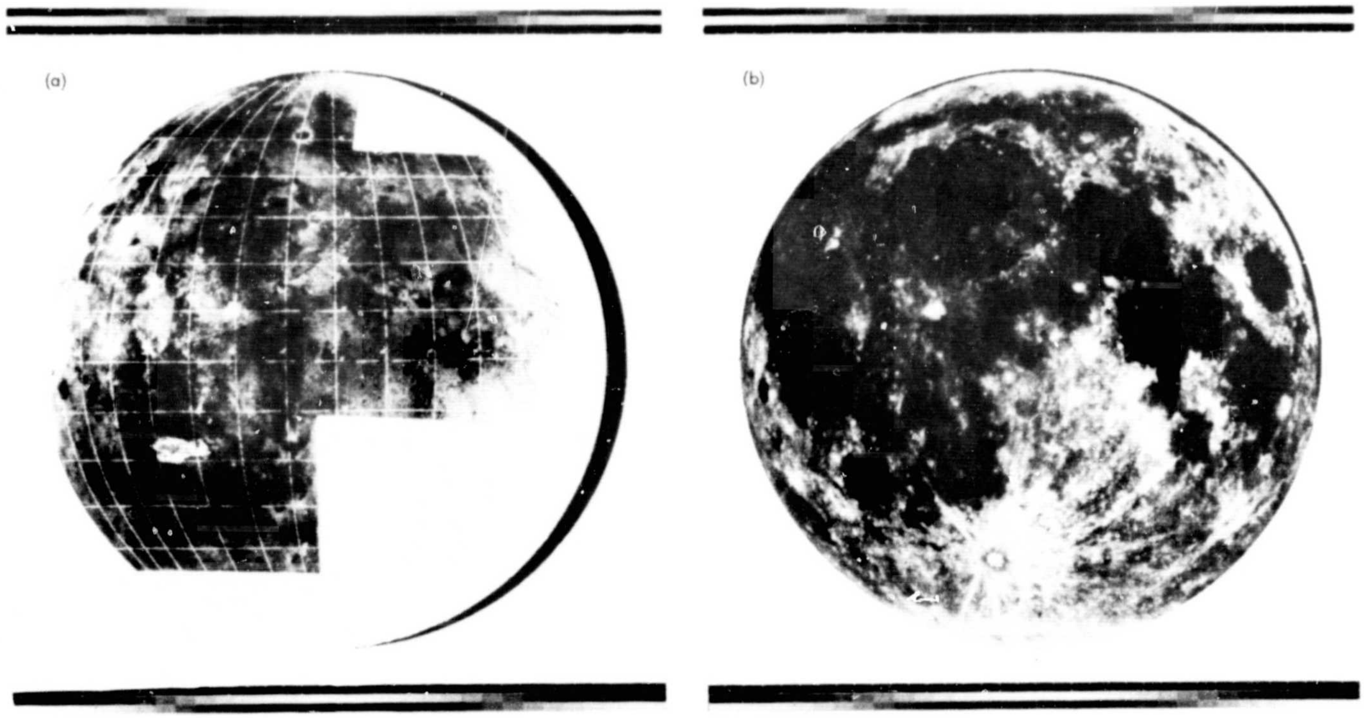

Fig. 4. Data sets for the S-217 Experiment: color-difference photography and full-Moon albedo (provided by E. A. Whitaker; see Ref. 17)

there a physical difference between the Cayley and Descartes geologic units? and (2) what is the nature of the bright units of the material of the Descartes Mountains? Our work showed that small differences in the 70-cm radar backscatter between the Cayley and Descartes formations suggested that the Cayley regolith is relatively free of meter-sized boulders to depths of 15 meters, which is the estimated thickness of the regolith at this landing site. A study of the remote sensing data and the Apollo photography of the bright Descartes region (between craters Descartes C and Dollond E) suggest that this is an asymmetrical ejecta mass with a different chemistry and a lower electrical loss. The Apollo photography with its higher resolution provided the evidence that the bright Descartes region was due to bright crater ejecta rather than a young volcanic deposit as suggested earlier by Head and Goetz (Ref. 20).

The Apollo 16 landing site provided another study by Zisk and Moore where 3.8-cm radar echo strength was compared with surface block counts from surface photographs (Ref. 2). They conclude that "substantial improvement in the prediction of surface and near-surface blockiness can be achieved by using Earth-based radar measurement." They note that "the Apollo 16 mission was the first opportunity to test hypothesized correlation between block frequencies and radar backscattering."

D. The Apollo 17 Landing Site at Taurus-Littrow

Studies of the Apollo 17 landing site and Mare Serenitatis were reported by Moore and Zisk (Ref. 6) and by Thompson, et al., (Ref. 5) in the Apollo 17 Preliminary Science Report (Ref. 21).

The early work trying to relate radar backscatter to surface blockiness was reported by Zisk and Moore (Ref. 2) for the Apollo 16 landing site. By the time that Apollo 17 had landed, more correlations between radar backscatter and surface blockiness were carried out. Apollo 17 surface photography produced more data, culminating in the report cited above. It is interesting to note that Zisk and Moore conclude that "comparison between echoes at the Apollo 16 and Apollo 17 landing site supports the postulate that factors other than small fragments and blocks produce differences in depolarized radar echoes." This postulate was tested further in studies of the larger areas, where many more radar scattering differences are explained by differences in surface chemistry.

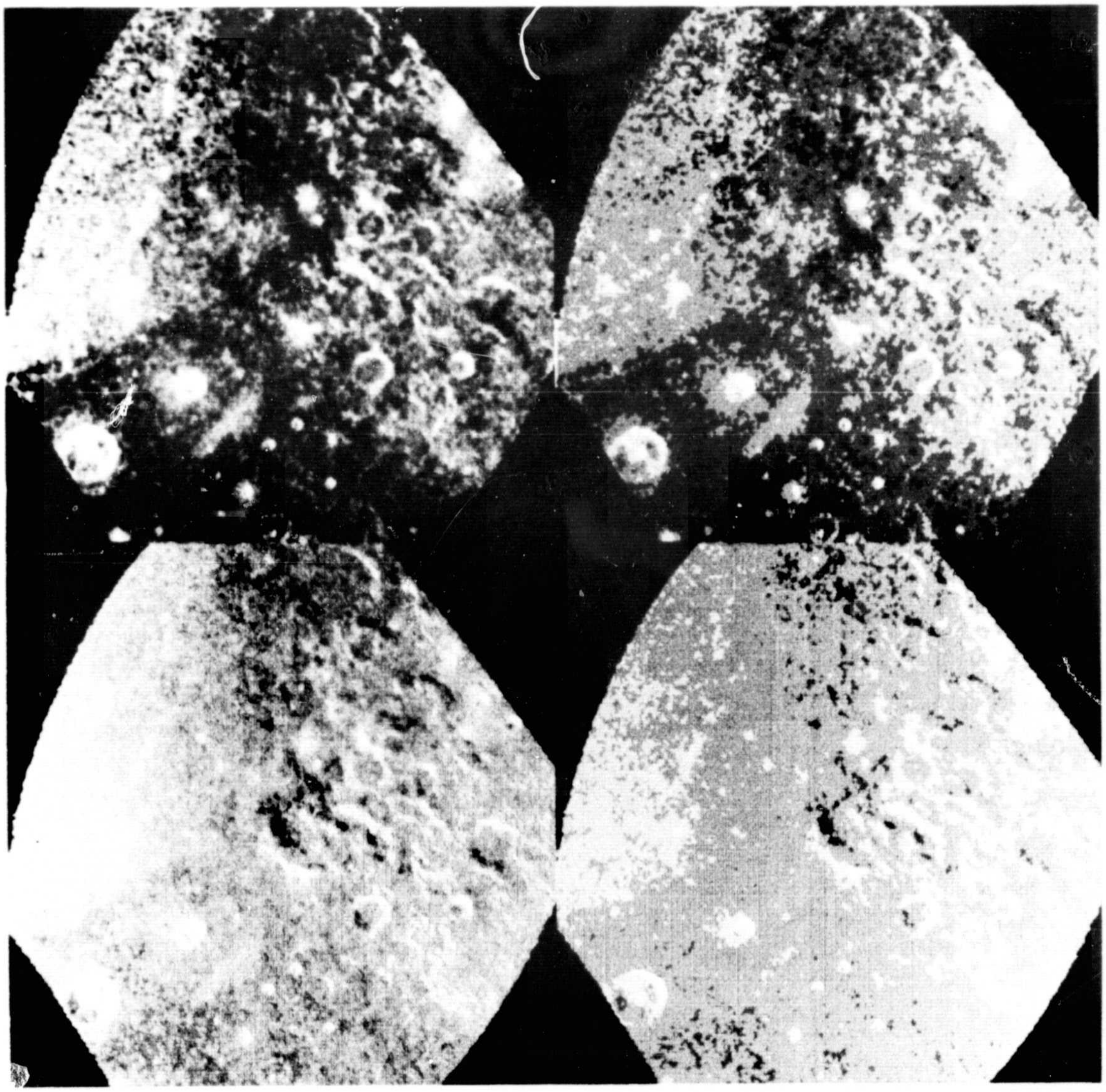

Fig. 5. Data sets for the S-217 Experiment: 3.8-cm polarized and depolarized radar maps (provided by S. H. Zisk; see Ref. 14)

E. Mare Serenitatis

Our attention to Mare Serenitatis was drawn by its proximity to the Apollo 17 landing site at Taurus-Littrow and by its unusual radar and color-difference signatures. The study of Mare Serenitatis differs from the landing-site studies in several aspects. The area bounded by 10° and 40°N latitude and by 0° and 35°E longitude, was much larger. The radar and infrared data were augmented by color-difference photography that made a crucial difference in the interpretation.

The remotely-sensed data for Mare Serenitatis permitted a separation of surface types as shown in Table 3. For the most part, these surface types agree with geologic units derived from the interpretation of orbital photography. The remotely-sensed data "see" surface types II and IV in the flat mare surface, the only indication of physical differences between eastern and western Mare Serenitatis. In other cases, the remotely-sensed data do not see differences between certain geologic units. This illustrates the complementary nature of the geologic interpretation and the determination of surface properties deduced from the remotely-sensed data.

A primary conclusion of the Mare Serenitatis work is that differences in surface chemistry are apparent in the remotely-sensed data. The radar backscatter from Mare

Table 2. Surface conditions inferred from infrared and radar observations[a]

Crater	Infrared (eclipse temperature)	3.8-cm radar enhancement	70-cm radar enhancement	Inferred surface	Geologic aging model	Occurrence
0	No	No	No	Normal distribution of rocks, old undisturbed surface	Asymptotic surface, provides basis for definition of anomalies: widespread	Most common
I	Yes	Yes	Yes	Excess number of centimeter- and meter-sized rocks	Predicted for recent cratering event	Common
II	Yes	Yes	No	Excess number of centimeter-sized rocks only: a very young and probably small feature	Behavior not predicted	Common
III	No	No	Yes	Older crater covered with a few meters of regolith	Predicted for cratering event of moderate age	Common
IV	Yes	No	Yes	Excess number of meter-sized surface rocks	Behavior not predicted	Rare
V	Yes	No	No	Excess number of smooth surface rocks much larger than meter-size, or smooth bare rock surface	Behavior not predicted	Rare
VI	No	Yes	Yes	Upper layer of regolith rough on centimeter and meter scale but no excess of bare surface rocks	Behavior not predicted	Rare
VII	No	Yes	No	Upper layer top of regolith rocky on centimeter scale but no excess of bare surface rocks: possibly, an excess number of surface rocks in 1- to 5-cm size range	Behavior not predicted	Rare

[a]Modified from Table I of Ref. 1.

Serenitatis correlates very well with color throughout the basin. However, radar-backscatter differences expected from different aged surfaces do not appear. Thus, chemical composition is a major controlling factor in radar backscatter for this area of the moon.

The Mare Serenitatis work also concluded that the remote-sensed data are useful for predicting lunar surface conditions beyond the areas covered by Apollo orbital photography. For example, the Mare Serenitatis study area included the LeMonnier Crater, the landing site of Lunokhod II (a surface sampler). Also, the southern rim of Mare Serenitatis has the same signatures as the Apollo 11 landing site in Mare Tranquillitatis. This suggests that the surface conditions and surface chemistry in southern Mare Serenitatis are the same as those observed for the Apollo 11 surface samples (collected some 400 to 500 kilometers to the south).

The Mare Serenitatis study area also provided an area for testing factor analysis as described later in Subsection III-H.

F. Imbrium Flows

The Imbrium Flows have provided another study using the Apollo photography and the remotely-sensed data. Our attention to this area was drawn by remarkably sharp radar-scatter and color-difference boundaries that appear in central Mare Imbrium.

An early report by Schaber (Refs. 22 and 23) concentrated on the geologic interpretation of Apollo orbital photography and identified the Euler β dome as the source of several late lava extrusions. A second report by Schaber, et al., (Ref. 7) concentrated on the interpretation

Table 3. Mare Serenitatis surface types defined by remote sensing data (modified from Table 33-I of Ref. 5)

	Surface type	Color	Albedo	Radar	Infrared eclipse temperature	Inferred chemistry
		1 = bluest 4 = reddest	1 = darkest 4 = brightest	1 = strongest 3 = weakest	1 = coolest 2 = warmest	1 = highest in titanium and iron 4 = lowest in titanium and iron
(I)	Southeast rim and Mare Tranquilitatis	1	2	3	2	1
(II)	Northwest Mare Serenitatis	2	4	2	2	2
(III)	Northeast rim, Southwest rim, Mare Serenitatis	3	3	3	2	3
(IV)	Eastern basin floor, Mare Serenitatis	4	4	1	2	4
(V)	Montes Haemus	4	1	3	1	4

of Apollo photography and the radar, infrared, and color-difference data. This second report concluded:

(1) Earth-based 3.8-cm and 70-cm polarized and depolarized radar return from Mare Imbrium decreases in average intensity from the old red to younger blue Imbrium age surfaces and also decreases from the oldest to youngest Eratosthenian surface, all of the blue spectral type.

(2) This reduced radar backscatter from the red to the blue Mare surfaces is attributed to increased radar absorption in the latter, resulting, at least indirectly, from increased titanium and/or iron content in the basalts and overlying regolith. The important physical/chemical parameter may be increased concentrations of disseminated ($FeTiO_3$) ilmenite opaques in a slightly deeper than normal glassy regolith.

(3) Titanium calibration of Earth-based radar backscatter maps should provide a powerful new tool for lunar geochemical and geologic mapping as well as providing a means for preliminary geological and geochemical analysis of Earth-based Venus backscatter maps.

G. Aristarchus Plateau

The Aristarchus Plateau provided another area where the interpretation of the Apollo photography was augmented by the remotely-sensed infrared, radar, and color-difference data. Our attention to this area was drawn by its very unusual red color, low radar scatter, and low infrared eclipse temperatures. Also, the Aristarchus region had very unusual orbital geochemical results and is often mentioned as the scene of transient events. The work on the Aristarchus Plateau is being prepared for publication by Zisk, et al., (Ref. 8).

The surface conditions on the Aristarchus Plateau were deduced from the collection of the remotely-sensed data, lunar orbital photography, lunar orbital geochemical experiments, and surface sampling experience. The synthesis of these data indicate that:

(1) The Aristarchus Plateau is most likely mantled by a pyroclastic material, which is fine grained with relatively few rocks of size material greater than 10 cm.

(2) The physical and chemical characteristics of this mantle material resemble the orange glass beads found at Shorty crater during the Apollo 17 surface sampling.

(3) The thickness of the block-free mantle must be between 50 and 300 m based on geologic interpretation of Apollo photographs and the physical explanations of the weak infrared and radar strengths.

(4) This mantle on the Aristarchus Plateau was deposited before the adjacent Eratosthenean Maria were extruded, based primarily on the interpretation of Apollo photography.

One of the striking results from this synthesis and interpretation of the Aristarchus Plateau data is that meaningful interpretations can be made for areas very distant from the lunar sampling sites. The Aristarchus Plateau is more than 1500 km from the nearest Apollo landing site and some 2400 km from the Apollo 17 landing site where the orange glass beads were found.

H. Factor Analysis Studies

At the University of Utah and the Boeing Co., R. W. Shorthill, W. J. Peeples and T. F. Greene (Boeing) studied the application of factor and cluster analysis techniques to multivariable lunar data sets. This work will be reported in a separate final report currently being prepared by R. W. Shorthill, et al., (Ref. 11.).

Factor analysis was applied to the Mare Serenitatis and reported by Peeples and Shorthill (Ref. 24). Four data sets were used including 70-cm polarized and depolarized echo strengths, albedo, and color difference. The observations were sampled every lunar degree from 17.6°N to 37.6°N latitude and 10.6°E to 29.6°E longitude for a total of 1600 observations at 400 grid points. This grid covers approximately 325,000 km^2 of lunar surface, an area large enough to determine whether the cluster analysis would quantitatively define surface units the same way as the previous qualitative studies of Mare Serenitatis by Thompson, et al., (Ref. 5).

These four data sets were first analyzed using an R-more factor analysis (Ref. 25). The results are shown in Table 4, which lists the principal factors and their components in terms of the four original variables. The three factors (F1, F2, and F3) retain 95.5% of the original data variance. Synthetic variable F1 was dominated by results from the 70-cm polarized and depolarized radar data, while F2 was dominated by the positive addition of the color difference data and albedo. F3 was a positive component of color-difference data and a negative contribution from albedo data.

Table 4. Results of R-mode factor analysis on Mare Serenitatis data

Factor No. / Experiment	F1	F2	F3
Color difference photography	0.281	0.725	0.628
70-cm radar (polarized)	0.906	−0.305	−0.013
70-cm radar depolarized	0.948	−0.083	−0.050
Albedo	0.196	0.776	−0.598
% variance accounted for by each factor	45.91	30.67	18.87

Based on our three synthetic variables (F1, F2, and F3), a new set of synthetic observations was created and the results were clustered (Ref. 26). Figure 6 shows that the results of this clustering yielded eight surface units.

The predominate cluster or surface unit in Serenitatis is denoted as unit 1. This unit delineates the central, high albedo, young unit of Serenitatis. Note that this unit appears to extend to the northeast into Locus Semniorum (Ref. 27). The second most predominate unit is labeled unit 2 and encompasses west central Mare Serenitatis. This unit is also detected on the eastern edge of the basin. The dark mantling material (Refs. 28 through 30) appears to correlate with unit 8 and is seen in the southwest corner of the basin extending northward and also appears to extend intermittently around the northeast margin of the basin.

Unit 3, which represents a unit associated with the dark annulus, is seen in the southwest, southeast, east, northeast, north and northwest borders of the basin, thus almost completely encircling the basin. Unit 4 occurs primarily along the northern border of the basin where it is intermixed with other units (predominately units 5 and 8). Unit 6 appears in the SE corner with a small patch in the SW corner. This unit also appears in the extreme NW corner of the basin. Unit 7 appears dominately in the SE quadrant of the basin with some material in the NW corner.

The similarity of this new factor analysis with the previous analysis is quite striking, except that our cluster

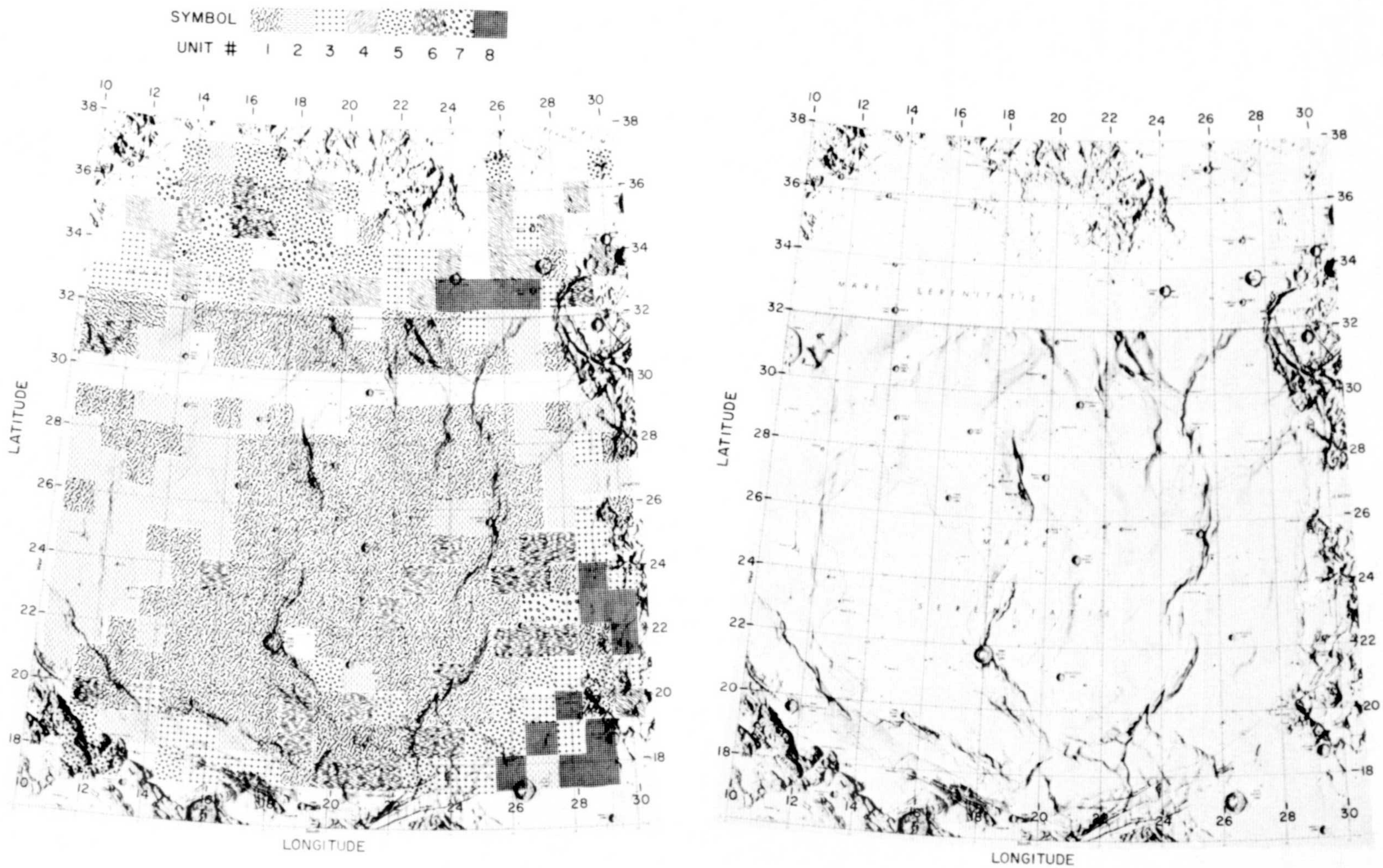

Fig. 6. Eight surface units in Mare Serenitatis determined by a factor and cluster analysis (taken from Fig. 3 of Ref. 24)

analysis surface types show more of the detail in the mapping that is actually inherent in the data. We were able to delineate (easily) eight surface types instead of the five types in the previous qualitative analysis.

I. Other Studies

Other studies were carried out under the S-217 experiment. Extensive correlations of photogeology with remotely-sensed data along the Apollo 14, 15, and 16 bistatic radar tracks were carried out by Moore, et al., (Ref. 9) and Moore, et al., (Ref. 10). These correlations will be reported in the final report on the S-222 experiment to be published by the United States Geological Survey by H.J. Moore. S.H. Zisk working with others at M.I.T. and Brown University coauthored scientific articles on the Lunar Black Spots (Ref. 31), Mare Humorum (Ref. 12), and lunar surface units (Ref. 32).

IV. Summary and Concluding Remarks

The results of the S-217 experiment indicate:

(1) Physical properties of the lunar surface such as small-scale (centimeter-sized) blockiness and surface chemistry (titanium and iron content) can be deduced by complementary geologic interpretation of Apollo photography and correlations between Earth-based infrared, radar, and color-difference mappings of the lunar surface.

(2) Much of the information in the Earth-based, remotely-sensed data pertains to surface properties on scales too small to be observed in orbital photography.

(3) Much of our interpretation of any lunar area is based on extrapolation of surface sampling experience.

(4) The geologic interpretation of orbital photography and the synthesis of remote sensing data are complementary. The geologic interpretation often limits our deductions of surface conditions from the remote sensing data; surface conditions deduced from the remote data often limits the geologic interpretations.

(5) Factor analysis, a modern statistical technique, successfully defined surface units from a complex, multivariable data set. This technique defined surface units that were not obvious by the visual overlay methods.

Appendix

Lunar Data Set Manipulations at the Image Processing Laboratory at JPL

The Image Processing Laboratory (IPL) at the Jet Propulsion Laboratory provided a valuable computer facility for manipulation and display of the Earth-based, remotely-sensed lunar data sets. An overview of the processing at IPL is given in Fig. A-1. Much of this IPL processing was accomplished by Lyman Lyon.

There are six prime data sets stored in digital formats at the IPL. These include digitized versions of color-difference and full-Moon photographs (provided by Ewen Whitaker), infrared eclipse temperatures and visible scans of the moon (provided by R.W. Shorthill), and 70-cm polarized and depolarized radar maps (provided by T.W. Thompson).

A convenient common projection for these data sets was to arrange the data in a square array where the horizontal and vertical position of a pixel (a picture element) was proportional to latitude and longitude (see Fig. A-2). Once the data was in this latitude-longitude format, it was easy to transform the data to other map projections. An IPL program, MPMERC, was written to transform the data to the Mercator Projections used for many Apollo Planning Maps. Examples of the lunar data in the Mercator Projection are shown in Fig. A-3 and in Ref. 33. Another IPL program, MPXSYS, was written to transform the data into orthographic projection, which shows the Moon at mean libration. Examples of the data in this projection is given by Figs. 2, 3, and 4, and by the figures used in the Mare Serenitatis article (Ref. 5). A combination of 1108 computer programs and standard IPL subroutines was used to transform the lunar data into the Lunar Aeronautical Chart (LAC) Projections as shown in Fig. A-4.

The base data sets for these projections are the data in the latitude-longitude array. These base arrays were obtained by several means. The 70-cm radar data was originally mapped to this latitude-longitude projection. The infrared and visual data sets from R.W. Shorthill were already digitized and the transformations from array position to latitude and longitude were already worked out. The color difference and full-Moon photographs provided by Ewen Whitaker were transformed to the base data set by a series of operations. First, the data were

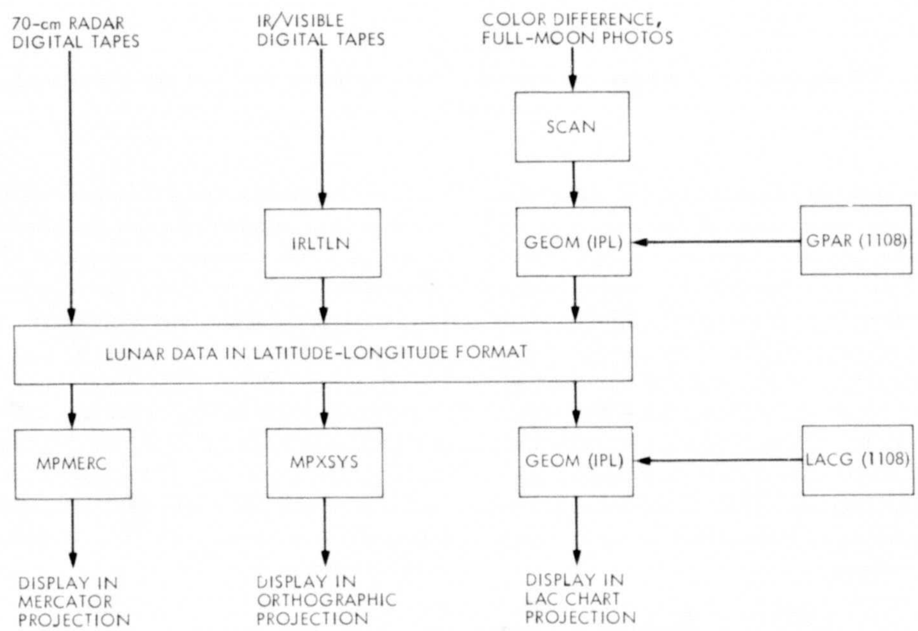

Fig. A-1. Overview of image processing of lunar data at JPL's Image Processing Laboratory

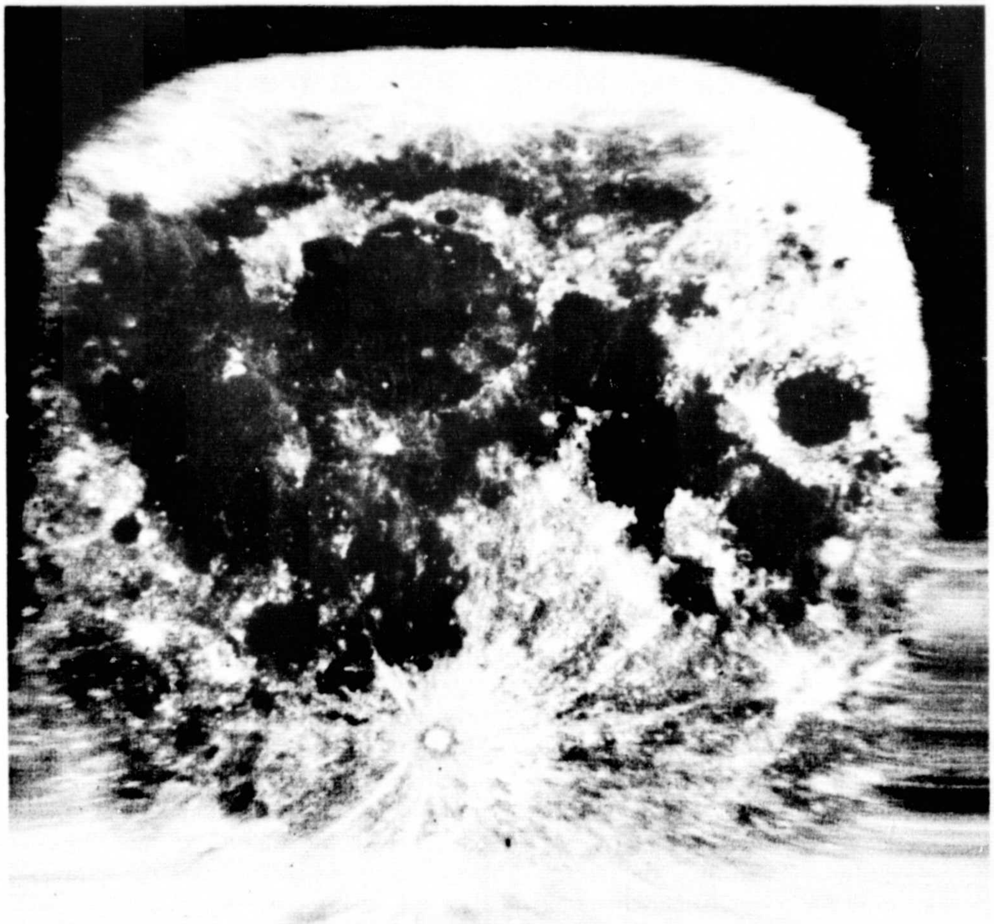

Fig. A-2. Example of a lunar data set in the latitude—longitude format: full-Moon albedo also shown in Fig. 4

scanned to convert the data into digital formats. After this scanning, the formulas for conversion of pixel position to latitude and longitude were computed by an 1108 computer program GPAR. Program GPAR punches input parameters for a standard IPL subroutine GEOM, which was used to convert the scanned data into the base set. Although these manipulations of the color-difference and full-Moon photos were more complicated than the other data sets, it left us with a powerful set of computer programs that could convert any scanned lunar data sets into a latitude-longitude array. This latitude-longitude array could be retransformed to the other standard map projections mentioned above.

Other computer programs were developed at JPL to accomplish a number of tasks peculiar to our S-217 work. A set of 1108 computer programs were developed to select data for points along the Apollo bistatic radar sets. This was used for the correlations along the radar tracks reported by Moore, et al., (Ref. 9), and Moore, et al., (Ref. 10). Another set of IPL programs was developed to printout statistics for areas within an IPL data set. These programs were used to generate the histograms that were reported by Schaber, Thompson, and Zisk (Ref. 7). Another set of 1108 and JPL computer programs were developed to redisplay the 3.8-cm radar maps at the IPL as shown in Fig. 5.

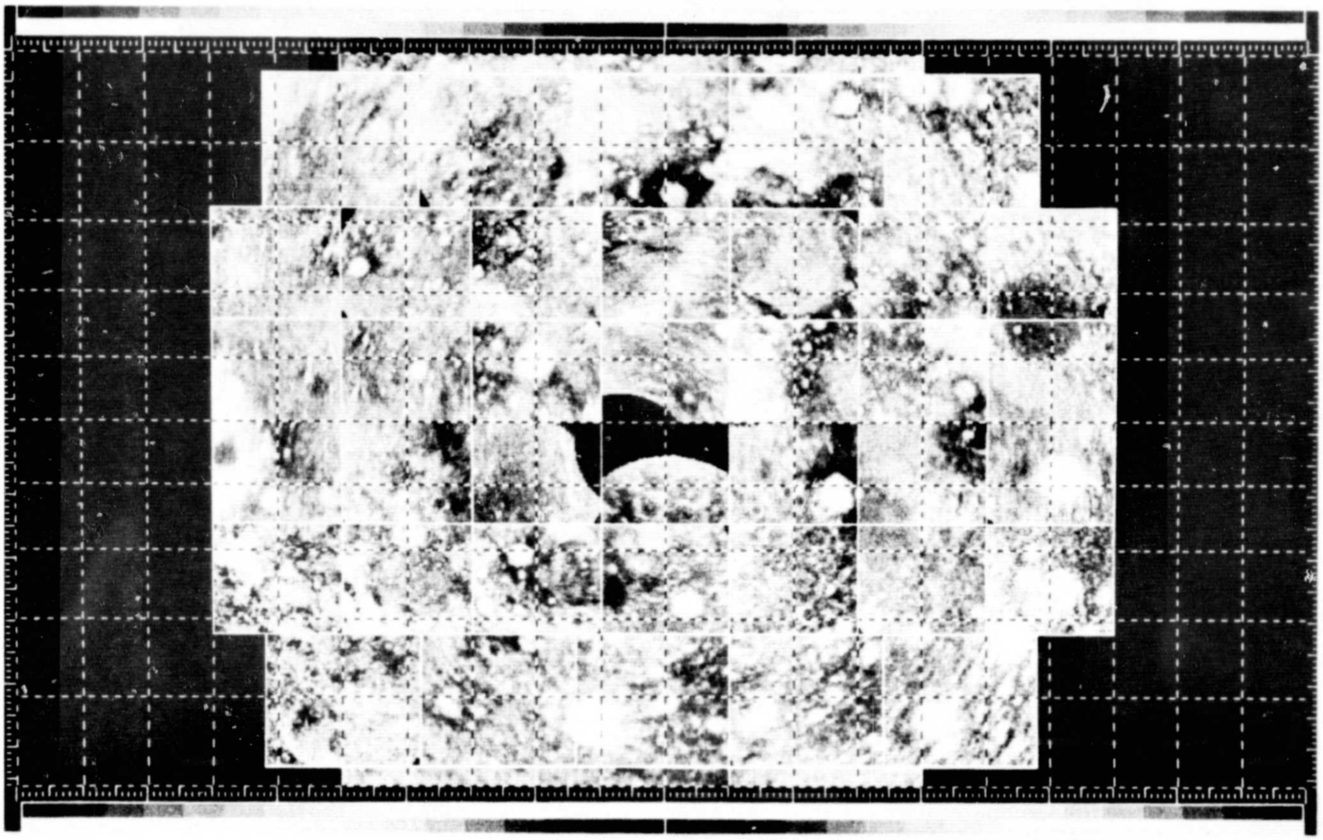

Fig. A-3. Example of lunar data set in the Mercator Projection: 70-cm radar echoes also shown in Fig. 2

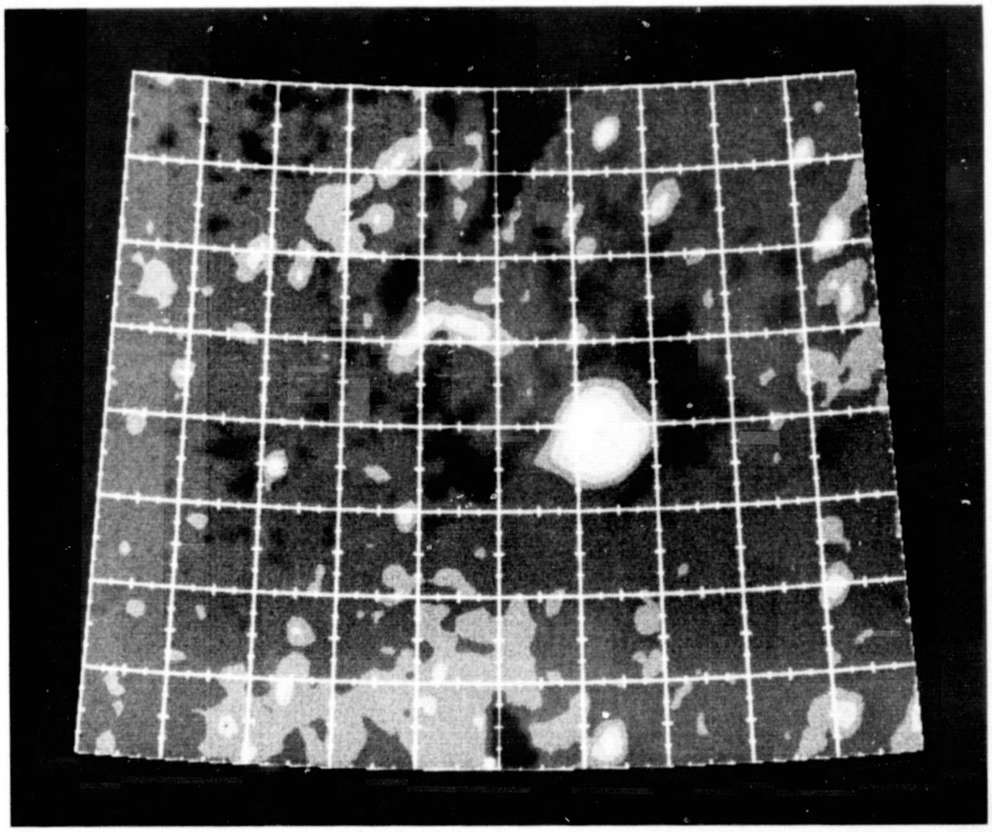

Fig. A-4. Example of lunar data transformed to Lunar Aeronautical Chart Projection: 70-cm depolarized data of the Aristarchus Plateau

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